

WATER IN FORESTS

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Summary

Recent results from four lines of research, all concerned in some respects with water, are discussed in relation to their silvicultural implications.

(1) **Interception loss from forests.** It has been shown that forests, by virtue of the turbulence they impose on the wind, lose a greater proportion of the intercepted rainfall by evaporation than is the case for smoother vegetation types. As a result, afforestation will reduce the water yield from catchments, the extent of the reduction being dependent on the pattern of rainfall.

(2) **Tolerance of roots to water-logging.** Recent research has demonstrated that Lodgepole pine, unlike Sitka spruce, modifies its root anatomy to enable diffusion of oxygen to active roots in anaerobic soil. Diffusion occurs through the xylem, there being a continuous space down the pericycle of primary roots while in woody roots there is a contiguous air-column in latewood tracheids.

(3) **Input and loss of nutrient elements.** By virtue of turbulent transfer, forests intercept from the atmosphere nutrients contained in aerosols, mist and fog, an input that together with that in rain largely compensates for nutrient removal in harvesting timber. Losses in leaching water are usually low, except following clear felling when nitrate losses may be high unless the site is allowed to vegetate rapidly.

(4) **Acid rain.** Damage to forests is only likely where concentrations of gaseous pollutants are high, as appears to be the case in parts of Germany where heavy damage has been reported. The acid rain received in Scotland is unlikely to damage trees but may reach streams and harm fish. Possible remedial measures that can be taken by the forest manager are suggested.

Introduction

Over the winter of 1978-79 the Silvicultural Group of the Royal Scottish Forestry Society discussed various active lines of research relevant to forestry in Scotland, and loosely linked under the general theme of "water." Discussions encompassed reports of reduced water yields from afforested catchments, modifications to tree root systems to enable survival in waterlogged soil, the input from the atmosphere of nutrient and pollutant elements as well as their subsequent loss to streams, and the related topic of acid rain. Since 1979 research developments have been extremely rapid and work in all four subjects has now reached a stage where a synthesis of the results is possible. Accordingly, this paper presents details of the original discussions, updated with information from recent literature. In addition, a final section has been added suggesting what action might be taken by silviculturalists in Scotland.

Forests and regional hydrology

Traditionally foresters have regarded trees as being the ideal cover for water catchment areas, on the grounds that by improving infiltration

they both reduce floods and prolong dry season streamflow. It came as something of a surprise, therefore, when Law (1956) published results from a study in Yorkshire which suggested that, in comparison with natural grassland, forest canopies reduce the yield of water from catchments. This stimulated a large programme of new research (McCulloch, 1982) that has now broadly confirmed Law's original predictions (e.g. Calder, 1979). The Centre for Agricultural Strategy (1980) in its recent report on the forestry industry suggested that there were constraints, in terms of reduced yield of water, to rather more than half the area potentially available for afforestation in Great Britain. They concluded, however, that "a blanket prohibition or acceptance of forestry is not an adequate answer: the hydrological characteristics of each catchment, the selection of sites for forestry, the pattern of land use and even the tree species chosen will affect the equation at each site."

In recent years considerable information has become available to explain the reduced water yield. Water is lost from a forest canopy by transpiration and by the evaporation of intercepted rainwater. These two processes require both the input of energy, to evaporate the water, and sufficiently dry air to receive further water vapour, expressed as the saturation deficit of the air. Clearly if the sun is shining, to provide energy, and the wind is blowing, so ensuring that the air around a leaf is continually changed before it becomes saturated, then both transpiration and interception loss will be high. This applies equally to grass and forest. In fact the amount of energy entering a grass sward is slightly less than that for a forest because grass reflects a greater amount of energy back into the atmosphere (higher albedo). However, because forests have a much rougher upper surface, the wind passing over and through them has a greater turbulence imposed upon it. The resulting eddies and accelerated winds ensure both removal of energy as heat from leaves and the continual replenishment of the air within the canopy with drier air from above.

Thus, the turbulent wind characteristic of forests is responsible, on the one hand, for reducing the energy available for evaporation but, on the other hand, ensures rapid removal of water vapour from around the leaf. This latter effect, the high boundary layer conductance, is most important when the canopy is wet, for it means that there is more rapid evaporation of intercepted rain water from a forest canopy than from a smooth grass sward, despite the cooler conditions (Table 1). Indeed, much of this evaporation can occur while the rain is still falling. The same efficient exchange of air should mean that transpiration is also higher from forests. However, as stomata close when evaporative stress is high, any such effect is prevented, so that transpiration from a dry forest canopy tends to be less than from grass, reflecting the cooling effect of the air turbulence rather than its effect on boundary layer conductance (Table 1).

The net effect of this enhanced loss from tree foliage when wet, and slight reduction when dry, seems to be an overall greater water loss from forests. Studies by the Institute of Hydrology in mid-Wales revealed that

loss from an afforested catchment was about 38% of the received rainfall whereas from a grassed catchment it was only 18% (Clarke and Newson, 1978). As the difference is due to evaporation from wet canopies, both the size of the canopy and the pattern of rainfall might be expected to be important modifying factors. In fact, there seems little reason to suppose that significant changes occur with alteration of the canopy, such as may result from heavy thinning (Kreutzer and Huser, 1978) or even, according to some authorities, from changing from coniferous to broadleaved species (Thom, in Clarke and Newson, 1978), although the long-term studies at Coweeta in North Carolina clearly show a greater interception loss beneath pine than beneath mixed hardwoods (Johnson and Swank, 1973). Most authorities agree, however, that the pattern of rainfall could be a significant factor. As Holmes and Wronski (1981) point out, interception loss from a forest receiving 100mm of rain in a month would be much greater if this arrives as 3.3mm per day, so maintaining an almost perpetually wet canopy, than if the rain arrived in 10mm showers every third day. Furthermore, comparisons quoted so far have all been with grass and refer to areas with little snow but with frequent rain showers. There remain incompletely answered questions relating to duration of wetness of the canopy, evaporation from snow and comparison with vegetation covers, such as heather or bracken, that can be rougher or more xerophytic than managed grassland. Hydrologists are well aware of these difficulties and research is expanding to cover a wider range of vegetation types.

TABLE 1

COMPONENTS OF WATER LOSS FROM DRY AND WET CANOPIES OF SCOTS PINE AND ADJACENT GRASSLAND MEASURED AT THETFORD FOREST
(from Jarvis and Stewart, 1979)

Cause of loss	Water loss (mm of rain)			
	Canopy Dry		Canopy Wet	
	Pine	Grass	Pine	Grass
Water deficit in air	3.09	1.14	0.59	0.03
Available energy	0.73	3.75	0.60	0.49
Total	3.82	4.89	1.19	0.52

Water at the rooting zone

Scottish foresters spend considerable effort trying to remove water from the rooting zone, so it is relevant to consider the detailed interaction of tree roots and excess soil moisture. In wet undrained soil anaerobic conditions develop which can lead to an accumulation of potentially harmful substances, such as hydrogen sulphide, reduced forms of iron and manganese, ethylene and various organic acids. Under certain circumstances one or more of these may be the direct cause of root damage, but it has now been fairly well established that the commonest problem is a simple lack of oxygen for the metabolic

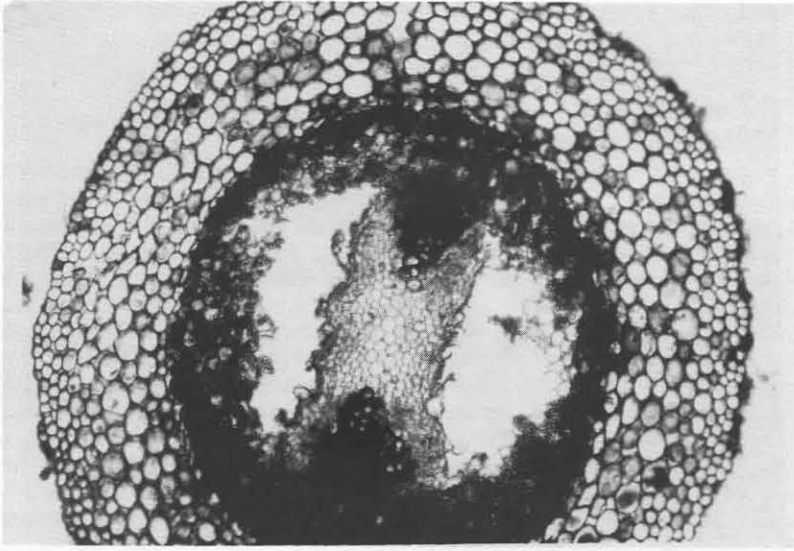
processes in the root (Sanderson and Armstrong, 1978). This then leads to interesting speculation as to the reasons for the clear differences between species, notably between Sitka spruce and Lodgepole pine, in their ability to withstand poor drainage.

Two general mechanisms have been suggested to explain tolerance of low oxygen concentrations. Firstly, plants may utilize alternative biochemical pathways in respiration thus reducing the accumulation of ethanol, a toxic substance that is normally produced by metabolic activity in the absence of oxygen. Flooded roots of Lodgepole pine have been shown to accumulate ethanol at a rate only a tenth of that in similarly treated Sitka spruce (Crawford, 1976). However, although this mechanism may be important in enabling roots to cope initially with anaerobiosis, it is insufficient to explain the continued growth of such roots, growth that is only possible if there is a readily available source of oxygen (Coutts and Armstrong, 1976). Accordingly, investigations have concentrated on a second possibility whereby roots, even in the absence of aerenchyma, can permit internal diffusion of oxygen. In 1972 Armstrong and Reid demonstrated that appreciable transport of oxygen did indeed occur in roots of pine seedlings, but not to any great extent in spruce. Since then the processes and modifications permitting oxygen diffusion in pine roots has been largely explained.

When young Lodgepole pine roots are flooded, particularly if this flooding occurs slowly, conspicuous spaces develop adjacent to the phloem in the pericycle of primary roots (Pl. 1), as a result of separation and collapse of the pericycle cells (Coutts and Philipson, 1978b). These spaces are continuous along the root and, provided the foliage or the upper parts of the root system of a seedling are exposed to the air, oxygen can diffuse down to roots subjected to anaerobic conditions (Philipson and Coutts, 1978). Furthermore, in woody secondary-thickened roots of pine, a continuous air column is found running through the tracheids of the latewood. Thus even in old trees air can enter through the lenticels of the shallow aerated roots and pass in the xylem down through roots of decreasing age and size to eventually reach the root tips (Philipson and Coutts, 1980). There is further limited oxygen diffusion within root bark of pine. Sitka spruce also shows some oxygen diffusion in bark but, unlike pine, seems unable to form continuous air passages within the xylem.

This is not to suggest that pine roots suffer no penalty when flooded. Mycorrhizal fungi seem unable to survive under anaerobic conditions in any species (Coutts and Philipson, 1978). Furthermore, flooding reduces radial growth of woody roots of even Lodgepole pine, so that with time there is a gradual diminution in the rate at which oxygen diffusion can occur (Coutts, 1982).

It is now possible to explain both the growth of roots in waterlogged soil and the reason why root survival is more prevalent on pine than on spruce. A related problem is the extent of root death that occurs as a watertable rises each winter, death that produces the typical "shaving brush" roots seen on windblown trees. Rapid flooding does not cause



Pl. 1. Transverse Section of Lodgepole pine root a few centimetres back from the apex showing the large cavities in the stele.

Photograph supplied by Dr M. P. Coutts, Forestry Commission, Northern Research Station.

sudden death of the root tips of either Lodgepole pine or Sitka spruce provided that these roots are already dormant, a state brought on by low temperatures (Coutts and Philipson, 1978a). If, however, the roots have not previously become dormant, considerable death may occur in pine, and in spruce very few active roots will survive. Even active roots show greater survival if they have already been exposed to cold soils, although the survival is less than that for dormant roots. It seems to be a regrettable fact that, in many British forests, temperatures do not fall fast enough in autumn to lower metabolic rates and induce root dormancy before the watertable rises.

Although soil moisture can increase rapidly in October and November (Pyatt and Craven, 1979) trees, because of their high interception loss, induce greater soil moisture deficits during the summer months than are found either beneath grass or heather. As a result, afforestation of peat soils can lead to considerable cracking. Usually these cracks only occur beneath the fibrous surface layer, which remains intact although with an increased bulk density. The cracks, which stretch down to the summer watertable level, essentially separate hexagonal pillars of shrunken peat that, on their surfaces, are often irreversibly dried and somewhat hydrophobic. Water runs readily through this network of cracks, except where these are blocked by a proliferation of tree roots. Research is now in progress to determine the extent to which this "natural" drainage system persists into the second rotation and whether there is any

silvicultural advantage in ensuring that the integrity and functioning of the system is not damaged during extraction and replanting.

Water and the input and removal of essential nutrients

INPUT OF NUTRIENTS

It has long been known that rain contains appreciable quantities of many essential nutrients. The importance of this has been the subject of intermittent controversy, although it was soon established that the amounts are small in comparison with the demands of intensive agriculture (Russell and Richards, 1919). More recently, attention has been drawn to the possible importance of rainwater inputs for low-intensity cropping systems, such as forestry (Ovington, 1962) and hill sheep farming (Robertson and Davies, 1965). As studies of such management systems continued, it became clear that inputs from the atmosphere can, indeed, be very significant. Furthermore, the input is higher than originally believed, for it is now known that the trapping on plant surfaces of mist, fine rainfall, dust and gases can lead to important inputs of some elements.

The additional input as a result of trapping on plant surfaces, variously called the filter effect of vegetation or interception deposition, is difficult to assess. A cylinder of polyethylene-coated netting placed over a rain gauge to act as an inert trapping surface, results in considerable increases in the concentrations of most elements in the collected rainwater (Table 2). These increases can be loosely correlated with the increases found beneath trees, but living vegetation, in addition to acting as a filter, also takes up nutrients by foliar absorption and releases nutrients into rainwater through the process known as crown leaching (Miller and Miller, 1980). Nevertheless, some attempts have been made to assess the magnitude of the interception deposition and it seems clear that for certain elements, notably potassium, it can be significant and even exceed the input in rainwater. Much of this additional input can be ascribed to sea salts and considerable increases in sodium concentration have been recorded in soil beneath newly established coniferous plantations in Britain (Potts, 1978; Williams *et al*,

TABLE 2

CONCENTRATION IN RAIN WATER COLLECTED BENEATH PLASTIC NETTING
IS A PERCENTAGE OF THE CONCENTRATION IN A STANDARD RAIN GAUGE
(100)

<i>Forest</i>		<i>Nutrient</i>		
		<i>K</i>	<i>Ca</i>	<i>Mg</i>
WEST COAST	Leanachan	160	250	390
	Kilmichael	270	120	270
	Kershope	270	200	430
	Strathyre	180	120	230
	Elibank	210	190	410
EAST COAST	Fetteresso	360	250	500

1978). However, the pattern of deposition across the country (Table 2) suggests that terrestrial dust is also important. Proximity to arable land and to a lime quarry have both been identified as contributory factors in the figures in Table 2.

Inputs of many elements, including iodine (Whitehead, 1975), lead (Reiners *et al*, 1974) and strontium (Graustein and Armstrong, 1983), are increased under trees as a result of this interception deposition. As the name implies, this process depends on similar mechanisms to those leading to the high interception loss of water from trees discussed in the first section. A fog droplet, or dry salt crystal, will normally be swept past any obstruction in a gentle wind, but the turbulent air flow within a forest provides the increased momentum to a particle to ensure that it penetrates the thin boundary layer of still air around the leaf and so impact on the surface (Chamberlain, 1975). Similarly, the turbulent air flow accentuates exchange of air between the canopy zone and the atmosphere above thus providing a continuous supply of droplets or particles within the canopy. A further aspect is that the chance of impaction is greatest on thin obstacles, for as target size increases the wind speed around it rises increasing the probability that any object will be swept past the target rather than penetrate the boundary layer surrounding it. This leads to interesting speculation as to the advantages of conifer needles over broad-leaves, or as to the consequences of differences in branch morphology between, say, birch and ash.

The impacted particles may be wet or dry, but both theory and experiment suggest that much of the input is in mist, fog or fine rain droplets (Miller and Miller, 1980). This is partly because fog droplets, being larger than most dry aerosols, have greater momentum and are more likely to penetrate the boundary layer around a leaf, and partly because a fog droplet is more likely to adhere to the leaf on impaction, whereas dry particles may bounce or be shaken off. It has been found that aerosol collection can be greater on hairy leaves than on hairless ones (Wedding *et al*, 1977). The processes of turbulent transfer and impaction, therefore, lead to greater inputs of fog droplets to forests (Schlesinger and Reiners, 1974). Concentrations of chemical elements are usually higher in fog, mist and cloud droplets than in falling rain or snow. Presumably this is because initial condensation is around a single sea salt crystal (condensation nucleus) and then as further water vapour condenses on the droplet there is a dilution of the ionic concentration until the growing droplet is no longer suspended but falls as rain (although in later stages droplets partly grow through coalescing). As a result of the higher chemical concentrations in small, suspended water droplets, Lovett *et al* (1982) estimated that in subalpine forests of New England, intercepted cloud water, which accounted for 46 per cent of the water reaching the forest, introduced from 60 to 80 per cent of the atmospheric contribution of several nutrient elements.

Thus, interception deposition can be large and might be expected to have ecological consequences. Art *et al* (1974) have suggested that the maintenance of high rates of primary production in a forest on poor

coastal sand was partly due to the input of base cations in salt spray, and Azevado and Morgan (1974) considered that the nutrient input in fog along the Californian coast is reflected in both species composition and soil characteristics. Kellman (1979), working in Belize, noted considerable enrichment of base cations in soils beneath clumps of trees in otherwise open savanna. He ascribed this enrichment to interception deposition and suggested that the process eventually enables invasion of the savanna by more demanding rain forest species. Similarly, from their studies on Corsican pine at Culbin, Miller *et al* (1979) postulated that enhanced input of nutrient elements from the atmosphere, coupled with effective retention within the ecosystem, may be the mechanisms evolved by coniferous trees to enable them to thrive on soils low in potassium, magnesium and, to a lesser extent, calcium and nitrogen.

TABLE 3

QUANTITIES OF NUTRIENTS INTRODUCED TO FORESTS IN RAIN, AEROSOLS AND DUST IN COMPARISON WITH AMOUNTS REMOVED IN HARVESTED PRODUCE

	kg ha ⁻¹ yr ⁻¹				
	K	Ca	Mg	N	P
INPUT IN RAIN					
Measured at eight Scottish sites ¹	2-6	3-27	3.1-11.1	4-22	0.02-0.17
Other European studies ²	1-20	1-17	0.5-4.7	8-22	0.04-0.50
TRAPPED AEROSOLS AND DUST					
Scotland ³	7	4	2.1	trace	trace
Germany ⁴	5	6	0.6	4	0.2
REMOVAL IN FOREST HARVEST ⁵					
Conventional harvesting					
YC 6	1	1	0.4	2	0.17
YC 16	3	4	1.2	6	0.58
Whole-tree harvesting ⁷					
YC 6	2	3	0.7	3	0.42
YC 16	7	7	1.7	13	1.24

1. Miller, Miller and Cooper, unpublished data

2. Hornvedt (1975)

3. Miller, Cooper and Miller (1976)

4. Mayer and Ulrich (1974)

5. Miller, Miller and Cooper (1980), values calculated for Corsican pine

6. Removal of only stem wood and stem bark at thinnings and clear felling over economic rotation

7. No thinnings, crop clear felled and all above ground components chipped when top-height reaches about 12.5m

Forests, therefore, because of the turbulence they impose on the wind, receive a high interception deposition on top of the quantities of nutrients arriving in rain (Table 3). The total derived from these two pathways of input would rarely be less than the quantities of nutrients removed in harvesting, even in the event of whole-tree harvesting becoming a viable technique. An exception to this generality is phosphorus, for which the atmospheric inputs are unlikely to

compensate for even low intensity harvesting losses and it must be supposed that the evolution of the mycorrhizal relationship, coupled with mineral weathering, are the main factors which ensure an adequate supply of this plant nutrient.

LOSS OF NUTRIENTS

Any input, whether from the atmosphere or through soil weathering, is only of value if the nutrients are retained within the ecosystem long enough to be taken up by the trees. Forests seem to be particularly effective at retaining received nutrients, a process that depends very much on uptake by the vegetation and is most pronounced for nutrients, such as nitrogen and phosphorus, that may be in short supply. A number of experiments with nitrogen fertilizers in northern forests have suggested high retention rates (Overrein, 1970; Miller *et al.*, 1976; Morrison and Foster, 1977). Fertiliser phosphorus is also efficiently retained, except in young forests on drained peat (Malcolm and Cuttle, 1983), and applied potassium has been shown to be still cycling through the trees up to 23 years after application (Stone, 1981; Stone and Kszystniak, 1977). An extreme example comes from the forests of Venezuela where less than 0.1 per cent of radioactive tracers of several nutrient elements applied to the forest floor leached through the root-organic mat (Stark and Jordan, 1978). Studies in Scotland certainly suggest that water draining from forests removes very small quantities of essential nutrients, other than the calcium and magnesium derived from soil weathering (Miller, Miller and Flower, unpublished data).

As nutrient retention within a forest ecosystem is largely dependent on tree uptake, it could be supposed that nutrient losses are most likely from old moribund forests or during the years after clear-felling and before the new crop has fully occupied the site (Vitousek and Reiners, 1975). Losses at these periods are more likely to be of importance with respect to contamination of streams than with respect to any long-term loss of soil fertility. This fear was brought into particularly sharp focus with the publication of results from the Hubbard Brook study in New Hampshire (Likens *et al.*, 1970) where very high nitrate levels were recorded in a stream during a three year period of blanket herbicide application following clear felling of a mixed hardwood forest. As these nitrate levels exceeded by several-fold the World Health Organization's recommended maximum levels in drinking water, the finding caused some concern and stimulated much new research. Fortunately, it has now been amply demonstrated (e.g. Kimmins and Feller, 1976; McColl, 1978; Sollins and McCorison, 1981; Haverlaen, 1981; Silkworth and Crigal, 1982; Krause, 1982) that provided natural revegetation with weed species is allowed to proceed, unlike the situation in the original Hubbard Brook study, then the nitrate peak is much reduced and of very short duration. The general pattern seems to be well understood and as revegetation is invariably rapid in British forests there seems to be little reason for concern. As recently stated by Vitousek (1981), it seems unlikely that additional input-output studies on manipulated catchments will add significantly to

our understanding; attention should now focus on systematic process studies.

A new and related environmental concern is the loss into streams of fertilizer phosphorus at a rate sufficient to cause algal blooms in reservoirs. Work by Harriman (1978) revealed an average annual loss of $2 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ following application of rock phosphate to Loch Ard forest. Although this quantity is small, it means that over the two to three years following application there was an approximately ten-fold increase in the phosphorus concentration of small streams. These concentrations frequently exceeded the maximum levels permitted for domestic water supplies under new EEC directives. Whether such concentrations would persist into reservoirs and there lead to harmful algal growth remains unknown. In view of the absence of reports of such damage in the past, despite the amounts of phosphate applied to the hills, this would seem unlikely. Some of the factors that lead to phosphate loss are already understood. Studies have shown that little phosphate is retained in peat (Cuttle, 1983; Malcolm and Cuttle, 1983), although it has long been known that mineral soils, as a result of their high contents of iron and aluminium, will retain virtually all the phosphate they receive. Loss into streams, therefore, could be expected to reflect the amount of peat on the catchment and the extent to which drainage water has passed through mineral soil before reaching the stream.

Clearly, no forester or upland farmer wishes to contaminate water supplies. Equally, forestry and agriculture in the uplands would be impossible without the use of phosphatic fertilizers. It is of paramount importance, therefore, that a dialogue be established to ensure minimum interference with the interests of both groups of users.

Acid rain

Acid rain has become an emotive subject. The term strictly refers to the acidity in rain, but the media now tend to use it to mean the rain of acidity, or more correctly total acid deposition. By this is meant the dry deposition of the acid-forming gases, sulphur dioxide (SO_2) and the oxides of nitrogen (NO_x), as well as the acids dissolved in rain (sulphuric acid and nitric acid derived from SO_2 and NO_x). Sulphur dioxide largely comes from the combustion of coal and oil whereas NO_x is produced mainly in internal combustion engines. The production of both gases has increased over this century, although clean air policies have largely eliminated heavy emissions of soot and ash (paradoxically, the ash would once have neutralised some of the acidity in combustion gases).

Close to an emission source deposition is largely of the dry gases. Some of the gas not deposited becomes entrained in clouds to form the acids that may eventually be deposited in rain, perhaps several hundreds of kilometres away from the original source. Three broad, and rather different, sets of problems have been ascribed to acid rain, the differences largely reflecting variations in the proportions of dry deposition and rain introduced acidity.

Close to very major sources, the concentration of gases is so high that foliage is directly damaged. Furthermore, the huge amounts of the gases and their derivatives being washed into the soil can cause intense soil acidification with some rather strange effects (Hutchinson and Whitby, 1977). Examples of such areas includes those around the nickel smelter at Sudbury, the oil sand extractors of Alberta and the brown coal power stations in Czechoslovakia. Such damage is very localised and is not relevant to the general acid rain debate. At a low level, similar problems still exist around many of the major industrial areas in Britain where it is well established that there are restrictions on the tree species that can be planted, but in these cases soil damage seems unlikely.

The next area of damage is in the forests of central Europe, damage that is popularly ascribed to acid rain. Indeed, an early hypothesis was that acid rain, in combination with dry deposited acid being washed down trees stems, was mobilizing soil aluminium (a well established response of soil to increased acidity) until this reached levels toxic to tree roots. However, many aspects of this hypothesis have still to be confirmed and there is reason to suppose that tree roots are not particularly sensitive to aluminium levels. Recently a rather more convincing proposition has been put forward in Germany (Prinz *et al*, 1982). Here it was noted that injury (severe yellowing of needles, very low foliar magnesium levels and death of shoots in the upper crown immediately below the top few whorls) is distant from industrial areas, is concentrated on west facing slopes above 600-800m, is found mainly on trees on open sites exposed to sunlight and can be dated to years with fine summers such as 1976 and 1980. These factors lead to the suggestion that the damage is due to a mixture of gaseous pollutants above the inversion layer, in particular ozone which is produced from NO_x under the influence of strong sunlight. This is supported by the observation that the areas of damage correlate with the concentration of photochemical oxidants and mist, and that in 1980 monthly ozone concentrations were very high. This idea is broadly supported by the independently-derived views of Binns and Redfern (1983) who, at the request of the Forestry Commissioners, visited Germany and concluded that the damage they saw was most probably due to an interaction of air-borne pollutants with climatic injury, above the level of winter temperature inversions, and was unlikely to be caused by rainwater acidity acting alone.

In Scotland, the combined effect of low production of pollutants, except in parts of the central valley, strong continuous winds and limited sunshine means that damage of the types described above is extremely unlikely. Scotland, however, although it receives rather small amounts of dry deposition is, like southern Scandinavia, subjected to rain of low pH, i.e. true acid rain. Rainwater pH averages almost 5.0 in the Western Isles, but acidity increases on moving east so that pH is below 4.3 on the east coast (Harriman and Morrison, 1981; Fowler *et al*, 1982; Miller and Miller, 1983).

Rain of the level of acidity presently received does not directly damage vegetation. There has been some suggestion that it may interfere with

reproduction in plants, such as bracken, with exposed reproductive systems (Evans and Bozzone, 1977), but no such effect has been observed in the field. The only established effect is an accelerated rate of crown leaching of many cations, but this has not been accompanied by any reduction in foliar nutrient concentrations nor in tree growth (Hornkvist *et al.*, 1980).

The possibility of an effect through the soil, leading to gradually declining tree growth, was one of the earliest fears (Jonsson and Sundberg, 1972). Attempts to demonstrate such an effect from ring-width analysis is difficult because of the confounding effect of cyclical variations in climatic factors. Recent attempts, including a reworking of the original Swedish data, have failed to reveal any growth decline that could be ascribed to acid rain (e.g. Abrahamsen *et al.*, 1977; Cogbill, 1977; Jonsson and Svensson, 1982).

There remains the question of whether there could be acidification of the soil over an even longer time-scale. When dilute sulphuric acid is added to soil the hydrogen ions supplied by the acid replace some of the base cations, notably calcium and magnesium, on the soil exchange surfaces. Because sulphate is fairly mobile in soil, these cations can move in drainage water as the dissolved sulphate salts, eventually passing into streams and leaving behind a somewhat acidified soil with reduced base status. However, with time the hydrogen ions in the soil will be neutralised by the release of fresh calcium and magnesium ions from the weathering soil minerals, a process that is accelerated by the introduced acidity. Much depends, therefore, on the amount, and rate of weathering, of the soil minerals in the profile. Bache (1983) has pointed out that the neutralisation capacity of weathering granite is almost infinite compared to the size of current acidity inputs. Thus, it seems unlikely that acid rain is significantly acidifying typical Scottish soils; rather it is marginally accelerating geological weathering processes. Indeed, the rate of acid introduction in rain is no greater than that which can be expected from plant growth (Nilsson *et al.*, 1982). There are undoubtedly a few soils that are so low in weatherable minerals that some detrimental effects from acid rain may occur. Suffice to say that such soils are uncommon, any harmful effect will be very slow to develop and Scottish rain generally contains sufficient magnesium to replace any leached by acid rain.

Provided acid rain mixes well with the soil, all the acidity is neutralised and the sulphate salts of calcium and magnesium (gypsum and Epsom salts) pass into streams. It is now quite clear, however, that in areas with slow-weathering rocks, rain-introduced sulphuric acid may sometimes pass into streams without being fully neutralised (e.g. Dovland and Semb, 1978). In such acid drainage water there may also have been some replacement of hydrogen by soil-derived aluminium, a combination that is particularly toxic to fish. Just how the small additional acid input in rain, given the large natural production and consumption of hydrogen ions within a forest ecosystem, reaches streams without being neutralised in the soil is not at all clear. The most likely explanation is that some

drainage water is flowing laterally within the organic layer (Reid *et al.*, 1981) or is being channelled through cracks in the soil thus bypassing the neutralising reactions in the mineral soil horizons.

There remains a further twist to the story that, so far, is uniquely Scottish and Welsh. Harriman and Morrison (1981, 1982), of the DAFS Freshwater Fisheries Laboratory, have noted that in the Trossachs, an acid rain area, streams draining forested catchments are more acid than those draining open moorland, and contain fewer fish. Several possible reasons have been put forward to explain this, including enhanced capture of acidic aerosols and SO₂ on tree surfaces or accelerated soil drainage as a result of soil physical changes induced by the trees. There is no suggestion that the trees create the acidity; indeed spruce crowns usually somewhat neutralise received acidity (Miller, 1983). Rather it seems that in acid polluted areas trees facilitate the passage of pollution-derived acidity into streams. This is clearly a matter that requires, and is getting, further detailed research.

Conclusions

Because of the turbulence that the aerodynamically rough surface of a tree canopy imposes on the air flow, evaporation is higher from forests than from lower vegetation types. Water yield will then be reduced if a catchment is afforested, the extent of the reduction being greatest in regions where rain falls as frequent small showers. There is little, if anything, the manager can do to alter this situation. Rather, it is a matter for intelligent and sympathetic dialogue between the harvesters of wood and of water to ensure sensible compromises.

Afforestation leads to considerable drying of soils, largely because of the greater interception loss but, in addition, some species, such as Lodgepole pine, have the ability to exploit saturated soil by ensuring rapid diffusion of oxygen within roots. The possibility of breeding to accentuate this ability has been raised (Coutts and Armstrong, 1976) and foresters have long been aware of the advantages of selecting appropriate species for wetlands.

The same process that leads to increased interception loss from trees is largely responsible for the greater input of chemical elements to forests from the atmosphere. On poor soils this can be an important input which, coupled with that in rain, is generally sufficient to compensate for the nutrient losses in harvested timber. It does seem that forests are usually nutrient accumulating systems. Paradoxically, the same factors that ensure high nutrient input will accentuate the inputs of atmospheric pollutants to forests in comparison with other ecosystems, including elements such as lead and, where concentrations are high, acids and acid forming gases.

Managed forests can be associated with pollution of streams through loss of fertilizer-applied nutrients, particularly phosphorus, of mineralised nitrogen in the form of nitrate and of sulphuric acid derived from acid rain. It is important to note that neither the phosphorus nor the acidity would reach the streams if drainage water has first to pass

slowly through mineral soil. Similarly, nitrate would not be lost if there was adequate active vegetation growth to retain it. There would then seem to be a simple solution open to the manager—drains should not enter streams directly but should stop some distance back, thus forcing the mineral soil of the riparian zone to act as a filter both to remove phosphorus and to neutralise acidity. In addition, if this narrow zone carries unmanaged vegetation there would be no danger that felling would lead to the production of excess soluble nitrogen close to streams (although alder, which is an intensely acidifying species, should be avoided in such strips). The retention of narrow unfelled strips along streams has already been advocated in the United States to minimize the environmental effects of clear felling (e.g. Hornbeck and Ursic, 1979). It will be appreciated that this suggestion is very similar, although for differing reasons, to that advocated by fish managers for the preservation of good fish stocks in forest streams (Mills, 1980). It is a simple, cheap and effective means of reducing and often eliminating those negative aspects of afforestation presently of concern to environmentalists.

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References

- Abrahamsen, G., Horntvedt, R. and Tveite, B. (1977): Impacts of acid precipitation on coniferous forest ecosystems. *Water, Air and Soil Pollution* **8**, 57-73.
- Armstrong, W. and Read, D.J. (1972): Some observations on oxygen transport in conifer seedlings. *New Phytol.* **71**, 55-62.
- Art, H.W., Bormann, F.H., Voigt, G.K. and Woodwell, G.M. (1974): Barrier island forest ecosystem: role of meteorologic nutrient inputs. *Science* **184**, 60-62.
- Azevado, J. and Morgan, D.L. (1974): Fog precipitation in coastal California forests. *Ecology* **55**, 1135-1141.
- Bache, B.W. (1983): The implications of rock weathering for acid neutralization. In *Ecological Effects of Acid Deposition*. National Swedish Environment Protection Board—Report PM 1636, pp. 175-187.
- Binns, W.O. and Redfern, D.B. (1983): Acid rain and forest decline in Germany. *For. Comm. Res. and Devel. Pap.* **131**. H.M.S.O., Edinburgh.
- Calder, I.R. (1979): Do trees use more water than grass? *Water Services*, Jan. 1979.
- Centre for Agricultural Strategy (1980): *Strategy for the U.K. forest industry*. CAS Report **6**, University of Reading.
- Chamberlain, C.C. (1975): The movement of particles in plant communities. In *Vegetation and the Atmosphere, Volume 1, Principles* (Ed. J.L. Monteith), pp. 155-203, Academic Press, London.
- Clarke, R.T. and Newson, M.D. (1978): Some detailed water balance studies of research catchments. *Proc. R. Soc. Lond. A.* **363**, 21-42.
- Cogbill, C.V. (1977): The effect of acid precipitation on tree growth in eastern North America. *Water, Air and Soil Pollution* **8**, 89-93.

- Coutts, M.P. (1982): The tolerance of tree roots to waterlogging. V. Growth of woody roots of Sitka spruce and Lodgepole pine in waterlogged soil. *New Phytol.* **90**, 467-476.
- Coutts, M.P. and Armstrong, W. (1976): Role of oxygen transport in the tolerance of trees to waterlogging. In *Tree Physiology and Yield Improvement* (Eds. M.G.R. Cannell and F.T. Last), pp. 361-385. Academic Press, London.
- Coutts, M.P. and Philipson, J.J. (1978a): Tolerance of tree roots to waterlogging. I. Survival of Sitka spruce and Lodgepole pine. *New Phytol.* **80**, 63-69.
- Coutts, M.P. and Philipson, J.J. (1978b): Tolerance of tree roots to waterlogging. II. Adaptation of Sitka spruce and Lodgepole pine to waterlogged soil. *New Phytol.* **80**, 71-77.
- Crawford, R.M.M. (1976): Tolerance of anoxia and the regulation of glycolysis in tree roots. In *Tree Physiology and Yield Improvements* (Eds. M.G.R. Cannell and F.T. Last), pp. 387-401. Academic Press, London.
- Cuttler, S.P. (1983): Chemical properties of upland peats influencing the retention of phosphate and potassium ions. *J. Soil Sci.* **34**, 75-82.
- Dovland, H. and Semb, A. (1978): Deposition and runoff of sulphate in the Tovdal river — A study of the mass balance for September 1974-August 1976. SNSF IR 38/78, 1978.
- Evans, L.S. and Bozzone, D.M. (1977): Effect of buffered solutions and sulfate on vegetative and sexual development in gametophytes of *Pteridium aquilinum*. *Amer. J. Bot.* **64**, 897-902.
- Fowler, D., Cape, J.N., Leith, I.D., Paterson, I.S., Kinnaird, J.W. and Nicholson, I.A. (1982): Rainfall acidity in northern Britain. *Nature* **297**, 383-386.
- Harriman, R. (1978): Nutrient leaching from fertilized forest watersheds in Scotland. *J. Appl. Ecol.* **15**, 933-942.
- Harriman, R. and Morrison, B.R.S. (1981): Forestry, fisheries and acid rain in Scotland. *Scott. For.* **35**, 89-95.
- Harriman, R. and Morrison, B.R.S. (1982): Ecology of streams draining forested and non-forested catchments in an area of central Scotland subject to acid precipitation. *Hydrobiologia* **88**, 251-263.
- Haverlaen, O. (1981): The effect of cutting on water quantity and water quality from an east-Norwegian coniferous forest. *Medd. Nor. inst. skogforsk.* **36**(7), 1-27.
- Holmes, J.W. and Wronski, E.B. (1981): The influence of plant communities upon the hydrology of catchments. *Agricultural Water Management* **4**, 19-34.
- Hornbeck, J.W. and Ursic, S.J. (1979): Intensive harvest and forest streams: are they compatible? In *Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling*, pp. 249-262. N.E. For. Expt. Sta., Broomhall, Pennsylvania, and State University of New York, Syracuse, N.Y.
- Hornvedt, R. (1975): Kjemisk innhold i nedbor under traer. SNSF Teknisk notat TN 18/75, Aas, Oslo.
- Hornvedt, R., Dollard, G.J. and Joranger, E. (1980): Effects of acid precipitation on soil and forests. 2. Atmosphere-vegetation interactions. In *Proc. Int. Conf. Ecological Impact of Acid Precipitation* (Eds. D. Drablos and A. Tollan), pp. 192-196. SNSF Project, Oslo, Aas.
- Hutchinson, T.C. and Whitby, L.M. (1977): The effects of acid rainfall and heavy metal particulates on a boreal forest ecosystem near the Sudbury smelting region of Canada. *Water, Air and Soil Pollution* **7**, 421-438.
- Jarvis, P.G. and Stewart, J. (1979): Evaporation of water from plantation forest. In *The Ecology of Even-aged Plantations*, Proc. Meeting Division I, IUFRO, Edinburgh, 1978 (Eds. E.D. Ford, D.C. Malcolm and J. Atterson), pp. 327-349. Institute of Terrestrial Ecology, Cambridge, U.K.
- Johnson, P.L. and Swank, W.T. (1973): Studies of cation budgets in the southern Appalachians on four experimental watersheds with contrasting vegetation. *Ecology* **54**, 70-80.

- Jonsson, B. and Sundberg, R. (1972): Has the acidification by atmospheric pollution caused a growth reduction in Swedish forests? *Research Notes* 20, Royal College of Forestry, Stockholm.
- Jonsson, B. and Svensson, L. (1982): *Studie över luftföroreningarnas inverkan på skogsproduktion. En uppföljning och revision av Jonssons och Sundbergs rapport 1972.* Sveriges landbruksuniversitet, Inst. för biometri och skogsindelning, Umeå. Rapport.
- Kellman, M. (1979): Soil enrichment by neotropical savanna trees. *J. Ecol.* 67, 565-577.
- Kimmins, J.P. and Feller, M.C. (1976): Effect of clearcutting and broadcast slashburning on nutrient budgets, streamwater chemistry and productivity in western Canada. In *Proc. XVI IUFRO Congress, Division I*. pp. 186-197. Oslo, Norway.
- Krause, H.H. (1982): Nitrate formation and movement before and after clear-cutting of a monitored watershed in central New Brunswick, Canada. *Can. J. For. Res.* 12, 911-930.
- Kreutzer, K. and Huser, H. (1978): Der einfluss der waldbewirtschaftung auf die wasserspende und die wasserqualität. *Forstw. Cbl.* 97, 80-92.
- Law, F. (1956): The effect of afforestation upon the yield of water catchment areas. *J. Brit. Waterworks Ass.* 38, 489-494.
- Likens, G.E., Bormann, F.H., Johnson, N.M., Fisher, D.W. and Pierce, R.S. (1970): Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. *Ecol. Monogr.* 40, 23-47.
- Likens, G.E., Bormann, F.H., Pierce, R.S. and Reiners, W.A. (1978): Recovery of a deforested ecosystem. *Science* 199, 492-496.
- Lovett, G.M., Reiners, W.A. and Olson, R.K. (1982): Cloud droplet deposition in subalpine balsam fir forests: hydrological and chemical inputs. *Science* 218, 1303-1304.
- Malcolm, D.C. and Cuttle, S.P. (1983): Fertilizers applied to drained peat. 1. Nutrient losses in drainage. *Forestry* 56, 154-174.
- Mayer, R. and Ulrich, B. (1974): Conclusions on the filtering action of forests from ecosystem analysis. *Oecol. Plant.* 9, 157-168.
- McCull, J.G. (1978): Ionic composition of forest soil solutions and effects of clearcutting. *Soil Sci. Soc. Am. J.* 42, 358-363.
- McCulloch, J.S.G. (1982): Forest hydrology—present position and priorities. In *Research Needs in Forestry*, pp. 38-47. University College, London.
- Miller, H.G. (1983): Studies of proton flux in forests and heaths in Scotland. In *Effects of Accumulation of Air Pollutants in Forest Ecosystems* (Eds. B. Ulrich and J. Pankrath), pp. 183-193. D. Reidel and Company.
- Miller, H.G., Cooper, J.M. and Miller, J.D. (1976): Effect of nitrogen supply on nutrients in litter fall and crown leaching in a stand of Corsican pine. *J. Appl. Ecol.* 13, 233-248.
- Miller, H.G., Cooper, J.M., Miller, J.D. and Pauline, O.J.L. (1979): Nutrient cycles in pine and their adaptation to poor soil. *Can. J. For. Res.* 9, 19-26.
- Miller, H.G. and Miller, J.D. (1980): Collection and retention of atmospheric pollutants by vegetation. In *Proc. Int. Conf. Ecol. Impact of Acid Precipitation* (Eds. D. Drablos and A. Tøllan), pp. 33-40. SNSF Project, Oslo, As.
- Miller, H.G. and Miller, J.D. (1983): The interaction of acid precipitation and forest vegetation in northern Britain. *Water Quality Bulletin* 8, 122-126.
- Miller, H.G., Miller, J.D. and Cooper, J.M. (1980): Biomass and nutrient accumulation at different growth rates in thinned plantations of Corsican pine. *Forestry* 53, 23-39.
- Miller, H.G., Miller, J.D. and Pauline, O.J.L. (1976): Effect of nitrogen supply on nutrient uptake in Corsican pine. *J. Appl. Ecol.* 13, 955-966.
- Mills, D.H. (1980): The management of forest streams. *For. Comm. Leaflet* 78, H.M.S.O., Lond.
- Morrison, I.K. and Foster, N.W. (1977): Fate of urea fertilizer added to a boreal forest *Pinus banksiana* Lamb. stand. *Soil Sci. Soc. Am. J.* 41, 441-448.
- Nilsson, S.I., Miller, H.G. and Miller, J.D. (1982): Forest growth as a possible cause of soil and water acidification: an examination of the concepts. *Oikos* 39, 40-49.

- Overrein, L.N. (1970): Tracer studies on nitrogen immobilization mineralization relationships in forest raw humus. *Pl. Soil* 32, 378-500.
- Ovington, J.D. (1962): Quantitative ecology and the woodland ecosystem concept. *Adv. Ecol. Res.* 1, 103-192.
- Phillipson, J.J. and Coutts, M.P. (1978): The tolerance of tree roots to waterlogging. III. Oxygen transport in Lodgepole pine and Sitka spruce roots of primary structure. *New Phytol.* 80, 341-349.
- Phillipson, J.J. and Coutts, M.P. (1980): The tolerance of tree roots to waterlogging. IV. Oxygen transport in woody roots of Sitka spruce and Lodgepole pine. *New Phytol.* 85, 489-494.
- Potts, M.J. (1978): Deposition of air-borne salt on *Pinus radiata* and the underlying soil. *J. Appl. Ecol.* 15, 543-550.
- Prinz, B., Krauser, G.H.M. and Stratmann, H. (198): *Waldschaden in der Bundesrepublik Deutschland*. LIS Berichte No. 28.
- Pyatt, D.G. and Craven, M.M. (1979): Soil changes under even-aged plantations. In *The Ecology of Even-aged Plantations*. Proc. Meeting Division I IUFRO, Edinburgh, 1978 (Eds. E.D. Ford, D.C. Malcolm and J. Atterson), pp. 369-386. Institute of Terrestrial Ecology, Cambridge, U.K.
- Reid, J.M., MacLeod, D.A. and Creaser, M.S. (1981): Factors affecting the chemistry of precipitation and river water in an upland catchment. *J. Hydrology* 50, 129-145.
- Reiners, W.A., Marks, R.H. and Vitousek, P.M. (1975): Heavy metals in subalpine and alpine soils of New Hampshire. *Oikos* 26, 264-275.
- Robertson, R.A. and Davies, G.E. (1965): Quantities of plant nutrients in heather ecosystems. *J. Appl. Ecol.* 2, 211-219.
- Russell, E.J. and Richards, E.H. (1919): The amount and composition of rain falling at Rothamsted. *J. agric. Sci.* 9, 309-337.
- Sanderson, P.L. and Armstrong, W. (1978): Soil waterlogging, root rot and conifer windthrow : oxygen deficiency or phytotoxicity. *Pl. Soil* 49, 185-190.
- Schlesinger, W.H. and Reiners, W.A. (1974): Deposition of water and cations on artificial foliar collectors in fir krummholz of New England mountains. *Ecology* 55, 378-386.
- Silkworth, D.R. and Grigal, D.F. (1982): Determining and evaluating nutrient losses following whole-tree harvesting of aspen. *Soil Sci. Soc. Am. J.* 46, 626-631.
- Sollins, P. and McCorison, F.M. (1981): Nitrogen and carbon solution chemistry of an old growth coniferous forest watershed before and after cutting. *Water Resource Research* 17, 1409-1418.
- Stark, N.M. and Jordan, C.F. (1978): Nutrient retention by the root mat of an Amazonian rain forest. *Ecology* 59, 434-437.
- Stone, E.L. (1981): Persistence of potassium in forest ecosystems: further studies with the rubidium/potassium technique. *Soil Sci. Soc. Am. J.* 45, 1215-1218.
- Stone, E.L. and Kszystniak, R. (1977): Conservation of potassium in *Pinus resinosa* ecosystem. *Science* 198, 192-194.
- Vitousek, P.M. and Reiners, W.A. (1975): Ecosystem succession and nutrient retention: a hypothesis. *BioScience* 25, 376-381.
- Vitousek, P.M. (1981): Clear-cutting and the nitrogen cycle. In *Terrestrial Nitrogen Cycles* (Eds. F.E. Clark and T. Rosswall), pp. 631-642. *Ecol. Bull.* (Stockholm) 33.
- Wedding, J.B., Carlson, R.W., Stukel, J.J. and Bazzaz, A. (1977): Aerosol deposition on plant leaves. *Water, Air and Soil Pollution* 7, 545-550.
- Whitehead, D.C. (1979): Iodine in the U.K. environment with particular reference to agriculture. *J. Appl. Ecol.* 16, 269-279.
- Williams, B.L., Cooper, J.M. and Pyatt, D.G. (1978): Effects of afforestation with *Pinus contorta* on nutrient content, acidity and exchangeable cations in peat. *Forestry* 51, 29-35.